Under Pressure: A Brief History of Pressure Suits Part 1

By Phillip Keane

For the most part of our history, we have not ventured too far outside of a very specific set of environmental conditions, optimal for human life. It wasn't until we began to explore the depths of the oceans in the 18th century, and then began to explore higher altitudes in the 20th century that we noticed the effects of pressure on human physiology. These new environments introduced variations in temperature and pressure that were far in excess of our comfort zone, up to the point of being fatal to those not properly equipped.

Pressure

Pressure, in hydrostatic terms, is the force exerted on a body from a column of fluid of a certain height. This principle applies to air as well as water. The pressure acts perpendicular to the body from all directions. So in any fluid, the pressure experienced is proportional to the product of ρgh, where ρ is the density of the fluid, g is the gravity and h is the height of the column of fluid. At sea level, the pressure exerted by the atmosphere above is equal to 1 atm, or 101.1 bar. As we traverse skywards, the height of the air column acting on the body decreases, and therefore so does the pressure experienced.

The opposite can be said for when the human body descends beneath the ocean surface: pressure increases as the depth increases, and because water is much denser than air, the pressure increases proportionally faster with respect to depth. As mentioned previously, we operate best in a very narrow margin of atmospheric conditions, and outside of these conditions, we need to bring a suitable environment with us to survive, and this is where the story of the pressure suit begins.

Humans operate best in a very narrow margin of atmospheric conditions

Siebe, Gorman & Co. Ltd. bolted diving helmet. – Credits: David L. Dekker www.divescrap.com

Diving

Although underwater diving and high altitude flight involve different extremes of the pressure spectrum, it is worth mentioning them both from a historical perspective, as the development of altitude suits, and later on, the space suit, both share a common design heritage to underwater diving equipment.

The very first aviation pressure suits resembled diving suits, as they were largely just modified versions of the sub-aquatic equipment. The most obvious commonality between the two types of suit is the need to create a fluid-tight seal, be it for water or for air, and George Edwards was the first to design a diving suit with a bolt-on helmet that prevented ingress of water. Previous designs relied on a helmet that was held in place purely by its own weight, which frequently resulted in the deaths of divers from drowning.

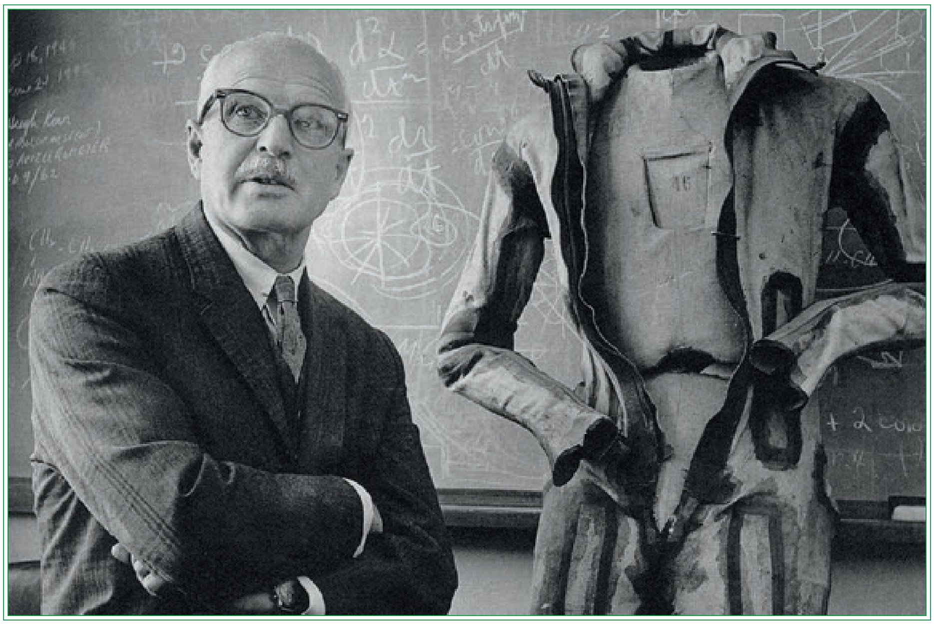
Development History

World War I saw the first widespread use of fighter craft in combat, and consequently pilots were subjected to high g-loads as well as exposure to altitudes above 4,572m as they strove to avoid enemy fire. Pilots reported loss of vision during high g maneuvres as well as headaches, dizziness, and fatigue. It was realized by medics that most of these symptoms were related to lack of oxygen at altitude, although the effects of acceleration were not realized until much later on.

The first conceptual pressure suit was designed after World War I by Fred Sample, an engineer from Florida, US. On 16th July 1918 he was awarded the patent for his "suit for aviators", that featured a bolt-on helmet, an oxygen hose that connected to a tank fitted on the back, and an inflatable gas-bladder which provided mechanical counter pressure to the lungs (much like the partial-pressure suits later designed). It was intended for pilots and mountain climbers. The suit was never manufactured, although it shared similarities with designs implemented in the late 1940's and 50's.

The first pressure suit ever manufactured was designed in 1931 by Evgeniy Chertovsky, a Soviet engineer working for the Aviation Medicine Institute in Leningrad. It was designed to protect the crew of Russian High-Altitude balloon experiments, but due to a catastrophic fire on the test balloon in 1935, it was never put to use.

Wiley Post in his full pressure suit.
Credits: US Air Force



Canadian Wilbur Rounding Franks with his "Franks Flying Suit," the first G-suit, with water filled bladders. – Credits: University of Toronto Archives/Jack Marshall Photography

The 1930's are often seen as a Golden Age for aviation, with various parties competing to achieve higher altitudes and faster speed records. Two such gentlemen were the Swiss physicists August Piccard and his associate Charles Knipfer, who on May 27th 1931 became the first human beings to reach the stratosphere using a balloon and pressurized gondola.

Meanwhile, in Massachusetts, USA, another daredevil explorer had his eye on the altitude record. Mark Edward Ridge, who had previous experience in skydiving, had realized that the weight of a pressurized gondola would affect the performance of the balloon, and came to the conclusion that in order to survive at these altitudes he would be better off surrounding himself with pressurized air in a more lightweight and close-fitting form.

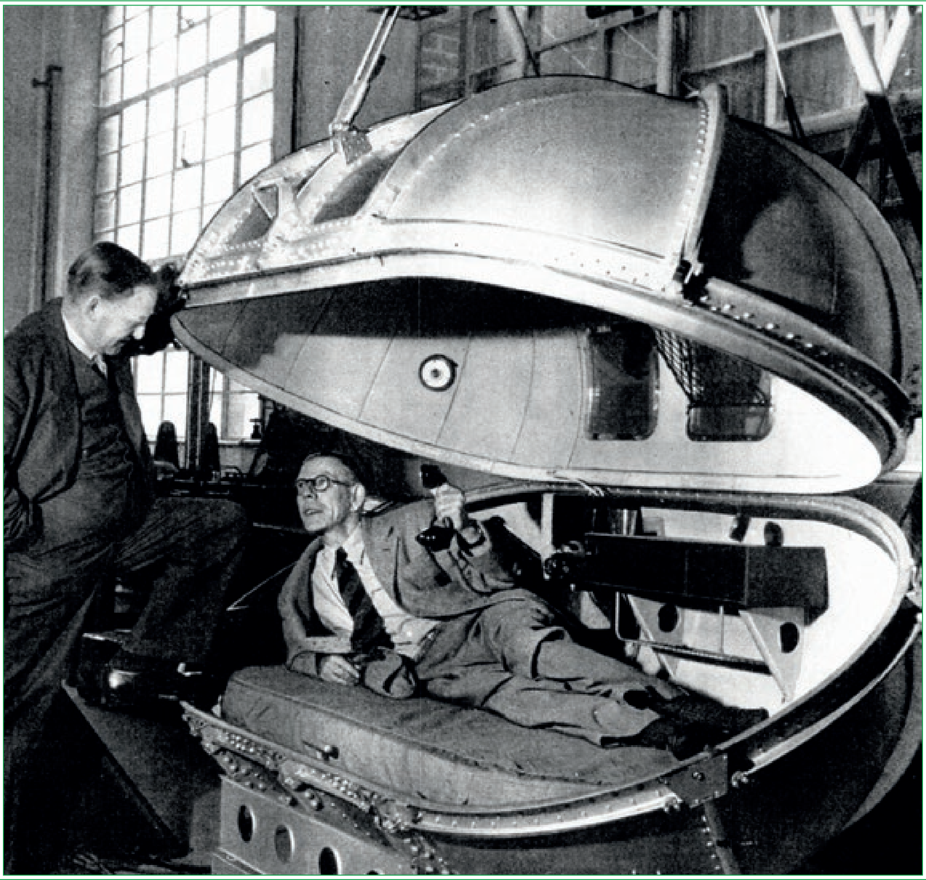
Ridge first turned to the US military for funding, but was refused assistance, so he then approached Dr. John Scott Haldane, a professor at Oxford University, UK. Haldane had previous experience working with pressure chambers as a researcher investigating the effects of decompression sickness in divers. Haldane also had experience of high altitude, as he led an expedition to the summit of Pikes Peak in Colorado, US, to investigate the effects of low pressure at high altitude.

Haldane had previously worked with Sir Robert Davis from Siebe Gorman & Company, an equipment manufacturer for deep sea divers. Ridge and Haldane approached the company with the Ridge design, and SG&C modified one of their diving suits to enable it to offer protection in a low pressure environment. This suit, made from rubber and canvas, was the first full pressure suit in history.

The first aviation pressure suits were modified versions of sub-aquatic equipment

The Ridge pressure suit was never tested in flight, but on November 16th 1933, Ridge became the first person to test a suit in an altitude chamber.

The honour of first flight in a pressure suit goes to an aviator by the name of Wiley Post. Post had already won several flight endurance awards and had realized that he could fly a lot faster at higher altitude, due to decreased air resistance. This reduced air resistance also meant that the piston engines of the time could not breathe enough oxygen to sustain combustion. This situation changed with the advent of the supercharger and other forced air induction systems. On August 30th 1934, Post became the first person to test an operational pressure suit in flight.



Winston Churchill's Personal Pressure Chamber was fitted to his personal aircraft, maintaining pressure at an equivalent of 1524m which enabled the ailing Prime Minister to travel above 2438m. – Credits: LIFE Magazine

During the remainder of the 1930's, several countries were developing their own suit designs in parallel, with a variety of different results. The German company Drager was working on hard-shelled full-pressure suits, but the lack of mobility provided by the metal suit rendered it useless for aviation. The lack of mobility caused by the pressurized suits ballooning was a design challenge that engineers would attempt to overcome for decades after.

World War II and G-suits.

One name that resonates through the history of aero medicine is that of Harry Armstrong, a physician in the US Air Force who investigated formation of gas bubbles in the blood and the necessity for prebreathing, examined toxic hazards in aircraft, and defined the point in the atmosphere known as Armstrong's Line: the altitude at which unconfined water on the human body would boil at body temperature.

As first observed during WWI, pilots

In 1934 Wiley Post became the first person to test a pressure suit in flight

were suffering from effects of blood pooling in the legs and from organ shifts inside the abdominal cavities. Armstrong discovered that by applying pressure at the extremities and at the chest that these effects could be prevented. There were several different concepts being tested at the time, all of which required a pressurized fluid contained within bladders positioned within the suit. The Canadians opted for water filled bladders, and the Australians, British, and Americans opted for pneumatic systems. Some systems required hand pumping for pressurization, while others used compressed air of the engine superchargers. It was during this period that the legendary David Clark

US Air Force pilot being equipped with air-bladder type anti-G suit. – Credits: US Air Force

company entered into the pressure suit business with the "T-1 model," and they have remained at the forefront of pressure suit design ever since.

At the end of the war, a new paradigm was about to emerge. With the invention of the jet engine by Frank Whittle and with developments in rocketry by the Germans, human endurance was about to be pushed to new extremes, never before experienced. The seeds of the Space Age had been sown, and the pressure suit manufacturers would be forced to change with the times.

To be continued in Part 2: The Jet Age, The Cold War, Apollo, and beyond.

The "Tomato Worm," one of the few full-pressure suits developed during WWII for US Air Force pilots. – Credits: US Air Force

Under Pressure: A Brief History of Pressure Suits Part 2

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In the previous issue, we examined the sub-aquatic origins of the pressure suit, effects of pressure and high acceleration on the human body, and the development of pressure suits until the end of WWII.

The Jet Age

Although the turbojet had been designed in parallel by English engineer Frank Whittle and German engineer Hans Von Ohain, jet engines were largely ignored until 1944, when the RAF and Luftwaffe began using jet aircraft operationally. Jet engines allowed for even higher acceleration than previous piston engines, and due to the compressors inherent in turbojets, allowed aircraft to fly at much higher altitudes where the air was less dense. This development meant that the human body would be subjected to stresses far greater than anything before, and required further innovations in pressure suit design.

The Cold War

Following the Second World War and the newly invented jet engine, the Cold War caused a surge of aviation development, including high speed and high altitude based projects such as the X-1, X-15, and the Lockheed Martin U2 programs. Pilots of the X-1 aircraft were the first to utilize the operational capstan pressure suits, specifically the S-1 and later the T-1. It was reported, however, that Chuck Yeager wore a standard flight suit for the first supersonic flight, as he didn't reach a sufficient altitude where a pressure suit would be needed.

The SK-1 spacesuit. – Credits: Mikhail Shcherbakov

During the late 1940s and through most of the 1950's, the US Air Force (USAF) and US Navy divided their efforts in terms of development. USAF focused largely on partial pressure suits for their fighter pilots whereas the Navy focused on developing full pressure suits with immersion protection for the pilots who ended up "in the drink." One such naval development was the Mark 1 Mod III Omni-Environmental full pressure suit, which was designed by BF Goodrich. This suit underwent many modifications over a 10 year period, and culminated in the Mark IV, which formed the basis for the suits worn in the next chapter of American pressure suit development: the Mercury program and the dawn of the Space race against the USSR.

> The Cold War caused a surge of aviation development

Orbit and Beyond

The 1957 launch of Sputnik-1 by the Soviet Union had caused panic in the American government, which resulted in the creation of NASA and ARPA the following year. The race to put a man into space began with initiation of the American Mercury program and the Russian Vostok program.

The Russians succeeded in placing Yuri Gagarin into orbit on April 12th, 1961. For the purpose of this spaceflight, the SK-1 spacesuit was developed by Russian company NPP Zvezda. The SK-1 was used on all Vostok missions, with a modified version, designated as SK-2, used for Valentina Tereshkova, the first woman in space. The SK-1 was a full pressure type suit, and was designed to keep the cosmonauts alive for up to 5 hours in the event of cabin pressure loss.

In March 1965, Alexey Leonov became the first man to perform an EVA from his Voskhod-2 spacecraft. Leonov used the SK-1 derived Berkut spacesuit, which contained additional life support equipment. At the end of the EVA, the suit ballooned due to the vacuum, which prevented Leonov from reentering the capsule. He was forced to bleed air out of the suit to enter the vehicle.

The American Mercury program ran from 1959 to 1963, and was also

Gemini suits were seen as adequate for the purpose until the Apollo 1 fire

directed towards putting a man into orbit. The Goodrich Mark IV suit was seen as adequate for that purpose. However, the subsequent Gemini and Apollo programs required EVA maneuvers, and therefore additional protection from temperature extremes and radiation.

For the Gemini missions, NASA worked with David Clark Company to create the G3C and G4C suits based on the suits used by the X-15 pilots. The Gemini suits were constructed of six layers of nylon, including an interior nylon bladder and Nomex.

America made its first EVA in June 1965 as part of the Gemini 4 mission. The G4C suit used on Gemini 4 was similar in construction to the G3C, except it contained extra layers of Mylar to aid with thermal insulation, and a visor to prevent blindness during EVA. The early versions of the full pressure helmet contained a plexiglass faceplate, whereas the later models used polycarbonate. These suits were used on all Gemini missions except Gemini 7, which used a stripped down version of the G3C, known as the G5C, to enable donning and doffing whilst on the longer duration mission. Additionally, the G5C featured a soft hood, which could be removed far more easily than the fiberglass helmets of the previous models.

For the initial Apollo Block 1 tests, NASA utilized a slightly modified G3C suit, which was given the designation A1C. The main innovation in the A1C was an inflatable "Mae West" device, which was necessary in case of emergency water landing following launch escape. The Gemini suits were seen as adequate for the purpose until the fire in Apollo 1 forced NASA to insist on fireproofing on the exterior of the suits. The contract for the Apollo suits was then awarded to ILC Dover, and the new Apollo Block II suits were designated as A7L. The A7L was used on all manned Apollo missions, as well as Skylab and the Apollo-Soyuz missions. Neil Armstrong described the suit as "tough, reliable and almost cuddly." The AL7 was the suit used during EVA on the lunar surface. Additional features on the EVA version included a micrometeoroid shield and cooling system, which interfaced with the astronaut's backpack. The A7L was used until the discontinuation of Apollo in 1975, and lent many of its features to high altitude flight suits in the same period.

Jim Lovell wearing the hooded G5C suit, prior to the launch of the Gemini 7 mission. – Credits: NASA

The Soviet Union had also been developing suits for their ill-fated lunar landing program. In 1967, NPP Zvezda began development of the semi-rigid Krechet-94 pressure suit. This suit weighed in at 90kg, and had an aluminum alloy torso with flexible arms. It also contained a rear entry system, to enable quicker donning and doffing, which also contained an integrated life support system. This rear entry hatch bears some resemblance to the rear entry system on the experimental Z-1 suit currently in development by NASA. At the same time, the Soviet Union began development of the Orlan spacesuit, which was designed primarily for EVAs in microgravity. Variants of the Orlan have been used on space stations ever since, and are still used today onboard ISS.

A Krechet-94 suit, showing the entry port and integrated life support system.
Credits: Richard Kruse, Historicspacecraft.com

Combat Edge

The high altitude U2 and SR-71 programs spawned a protective garment that evolved into the partial pressure Launch Entry Suit, and later the full pressure Advanced Crew Escape Suit (ACES), both of which were used on the Space Shuttle. These Shuttle suits were designed and manufactured by the David Clark Company. A modified version of the ACES suit is being developed for use on the future manned Orion missions. The ACES suit is also similar in design to the Russian Sokol suit, which is used by astronauts who fly on board the Soyuz. Both the ACES and Sokol are intended to protect the crew in the event of cabin pressure loss, and are unsuitable for EVAs.

The 1970s saw the rise of the 4th generation of fighter jets, including the F-15 and F-16. What was remarkable about these aircraft was their high thrust to weight ratios, which enabled the aircraft to perform perfectly ▸▸

NASA astronaut Rex Walheim undergoes a fit check of his Sokol spacesuit in 2011.
Credits: NASA

vertical climbs for sustained periods of time, meaning loads of +9-Gz, and rapid ascent to high altitude. The ultra maneuverability of these new aircraft meant pilots required new garments allowing extra levels of protection as well as increased flexibility to operate the planes.

These new requirements led to the creation of the Tactical Life Support System development program, which combined g-suit garments with pressure breathing equipment in a single ensemble, as opposed to previous efforts that focused on developing separate garments. In addition to the acceleration and altitude protection, the program aimed to equip the suits with NBC protection (Nuclear Biological Chemical), liquid cooling garments, and thermal flash protective goggles. Several different ensemble variations were presented to the USAF; however, the final suit selected for operation consisted of an extended pressure-vest/torso garment, a modified CRU-73 regulator, and a CSU-13B/P type g-suit. This ensemble would ultimately evolve into the Combined Advanced Technology Enhanced Design G-Ensemble, also known as "Combat Edge."

The Combat Edge ensemble is still used by fighter pilots today, although its efficiency and safety has been questioned in the light of several recent F-22 Raptor incidents, where pilots have experienced hypoxia-like symptoms. Initial reports had pointed to a fault in the breathing regulator/anti-g (BRAG) valve, that forces the vest to remain inflated, even when the pilot is not undergoing heavy g-loads. It is suspected that this garment is forcing the pilots into a state of shallow breathing, which in turn causes hyperventilation. The root cause has not yet been completely established, although investigators will be looking into all protective garments worn by F-22 pilots. Whatever the result of the investigation, given the fact that in the early 1970s pilots were still wearing pressure suit and g-protection countermeasures which had their roots in WWII technology, it may be a good time to ask why 21st century fighter pilots are wearing technology that was developed for 1970s aircraft.

Neil Armstrong described the A7L as "tough, reliable and almost cuddly"

The series continues in the next issue, where we will look at the future of pressure suits, including NASA's Z-1 and the Biosuit.

F-22 Raptor pilots have had a spate of incidents in which overinflated vests caused hypoxia-like symptoms. – Credits: US Air Force

Under Pressure: A Brief History of Pressure Suits Part 3

By Phillip Keane

The Future

In the last issue, we looked at high speed, high altitude aviation, the dawn of the space race, and the pressure suits that kept the pilots and astronauts alive in those extreme environments. We also noted that pressure suit design is a long process, and that the state of the art of aerospace vehicles can often overtake that of pressure suits, meaning that pressure suit design really hasn't changed in over half a century. In this chapter, we will look at the future of pressure suit design.

Spacediving

One of the better publicized developments in recent history came from the David Clarke Company that designed and manufactured the suit worn by Felix Baumgartner for the Red Bull Stratos project. On 14th October 2012, Baumgartner completed his historic jump from 38.969 km and became the first man to break the sound barrier without the aid of an engine. Baumgartner ascended in a pressurized gondola and utilized a custom pressure suit made by the David Clarke Company for his descent. As skydivers require visual cues from their environment, the Red Bull suit featured mirrors and a heated visor to defog the screen from breath-induced condensation. The suit was both flame retardant and offered thermal protection in the range of +37°C to -67°C. To aid stability, the suit contained a drogue parachute and sensors that would deploy the chute in the event that its wearer lost consciousness. In addition to accelerometers and gyros for measuring linear and angular acceleration, pressure sensors were routed through a controller which regulated the pressure within the suit according to altitude. It is hoped that the information gleaned from the jump will aid development of fighter pilot suits for use in the event of high-altitude bail out.

> The Z-1 is the first officially endorsed NASA suit design in 20 years

Felix Baumgartner stands in his pressure suit right before his 14 October jump.
Credits: Red Bull Content Pool

ILC Dover: Still Going Strong

Since the design of the Space Shuttle's semi-rigid EMU (Extravehicular Mobility Unit) suit in 1980, ILC Dover has supplied an unbroken run of innovative designs. In 1988, the company unveiled the developmental ILC Dover Mk III, which featured a rear-entry system for more rapid entry than the waist-entry EMU suit. The high operating pressure (57 kPa) of the Mk III would enable astronauts to transfer from a pressurized air environment, such as a space station, into an oxygen rich suit without a pre-breathe required to avoid the bends. The combination of hard and soft materials enabled a wider range of motions, including bending fully at the knees, than early Apollo and EMU suits. Despite the success of tests, this suit was never used in space, as NASA favored an even more flexible soft suit option.

I-Suit

Design features from the Mk III carried over to the I-Suit. Development started in 1997, with the first generation waist-entry suit being delivered the following year. The second generation featured improvements and included a rear-entry system, a redesigned helmet for greater visibility, and weight reduction measures. A heads-up display was incorporated into the helmet and GPS functionality added. The I-Suit was developed for planetary excursions, using fewer heavy bearings and more soft fabrics to minimize the weight. The I-Suit featured a pure oxygen breathing system, water cooling, and was pressurized to 29.6 kPa, which also allowed for greater mobility.

NASA Z-Series

The Z-Series is the culmination of the previous efforts of ILC Dover. The Z-1 was the first prototype in the Z-series, revealed in November 2012; it is the first officially endorsed NASA suit design in 20 years. Z-1 is a full-pressure design with power supply, CO_2 scrubbers and thermal control. It features a rear port intended to connect to a docking port on a Lunar or Martian ground vehicle. This will prevent astronauts from bringing contaminants such as abrasive lunar regolith or toxic Martian soil into the vehicle. The port will enable astronauts to don the suit much faster than is possible with current suit designs. With the suit at the same pressure (57.2 kPa) and gas mixture as its connected vehicle, there will be no need for the user to pre-breathe oxygen before an excursion. ILC Dover has already won the contract to design the Z-2. If all goes well, the best elements of both suits will be combined into the production level Z-3, to be tested on the International Space Station in 2017.

Constellation Suit

The Constellation Space Suit System (CSSS) concept was designed by Oceaneering, a company that previously specialized in deep-sea exploration technologies. This was the first NASA award to a company outside the "big 3" suit makers. The CSSS has two configurations: an IVA soft-suit, similar in design to the ACES pressure suit, which could be worn during launch and reentry operations for protection in the case of cabin pressure loss and a hard shelled mode for EVA use, providing protection from micrometeoroids, radiation, and abrasive lunar dust. The suit was originally intended to be worn by the Orion capsule crew, but development was axed along with the majority of the Constellation Program.

The ILC Dover Z-1 prototype suit, which NASA plans to test on the International Space Station in 2017. – Credits: NASA

The ILC Dover Mk III is tested by Desert Research and Technology Studies (RATS) team in Arizona Desert. – Credits: NASA

Mechanical Counterpressure Suits

Earlier segments in this series explored the design flaws that have traditional space suits, largely due to pressurization needs. The gas envelope within the suit can cause a ballooning effect when worn in a vacuum environment that restricts the wearer's movement, as well as tiring astronauts due to the extra effort required to perform each motion.

In 1959, whilst working on the Mercury project, German born engineer Hans Mauch and his team noticed that when a closed cell foam was subjected to lower than ambient pressures, the cells within the foam would expand. When contained in a tight-fitting outer garment, this expansion would provide a force perpendicular to the body surface. This effect was similar to that utilized by the gas and fluid filled bladders in g-suits. Thus, the concept of the Mechanical Counterpressure Suit (MCP) was born. The system was developed further as part of the X-20 DynaSoar project, but was abandoned in 1962 when the suit was shown to be less mobile than predicted.

The advantages of the MCP largely stem from elimination of gas pressurization. Contrary to popular belief, exposure to hard vacuum does not cause the body to explode but tends to make the body swell and expand, and take on the appearance of a bodybuilder. The elastic fabrics of the MCP would apply pressure to the body to counteract the swelling, keeping the astronaut alive. Additionally, due to the soft materials used, if the astronaut were to get hit by a micrometeoroid then the damage would be localized to the impact area, and would not result in a rapid decompression as would be the case in a gas pressure suit.

The development of improved fabrics spurred NASA engineer Paul Webb to revisit the concept of the MCP, and in 1968 he published an article in Aerospace Medicine that attracted positive attention from the industry. Now referred to as the "Space Activity Suit," and described as an "elastic leotard for Extravehicular activity," contracts were awarded for the development of the new suit. The Space Activity Suit was tested in vacuum chambers, with puncture holes up to 1mm in diameter and showed no lasting harmful effects to the wearer, aside from a small blemish which faded quickly.

The concept had been validated, but due to problems with maintaining constant pressure over the joints in the body, the program was dropped, and research into MCPs all but stopped for nearly thirty years. ▸▸

The advantages of the MCP largely stem from elimination of gas pressurization

Bio-Suit

It is apparent that future visitors to Mars will be involved in strenuous physical activities that require a more agile space suit than the current state of the art allows. For this purpose, Prof. Dava J. Newman at MIT has been working on an updated version of the MCP, aka the “Bio-Suit.” Like the MCP predecessors, the Bio-Suit is also a skin-tight garment, but where the previous versions were made from foam, the Bio-Suit uses a fabric woven into a 3D matrix. The lines visible on the exterior of the suit are elasticated, and follow lines of non-extension over the body. The matrix acts in compression and tension, exerting a constant mechanical pressure over the body, but unlike previous iterations, the Bio-Suit retains equal pressure over joints, even when they are bending. Professor Newman is an expert in the field of biomechanics, and in particular has extensive experience in the use of computers for monitoring body movements, a critical factor in overcoming the shortfalls of prior MCP suits. Similar to previous designs, the Bio-Suit can withstand small punctures without risk of rapid decompression, and the punctures can be healed immediately with strips of elasticated fabric, providing the wearer time to return to the safety of a pressurized environment.

Skin-tight space suits have been a staple since the early days of science fiction for various reasons, ranging from aesthetics to advanced mobility. Buck Rogers wore one in the early comic books, and a similar garment called the “walker” was used for exploration of the Martian surface in Kim Stanley Robinson’s Mars Trilogy. In a lot of respects, the Bio-Suit seems to be making the transition from art into reality...or it was. Like most of the innovative designs in this chapter, development of the Bio-Suit has been put on hiatus.

The Ideal Suit

The ideal suit should be easy to don and doff and provide protection for intra- and extra-vehicular activities, both on planet and off. It should be lightweight and mobile, yet should offer protection against radiation, micrometeoroids, dust, and temperature extremes. It seems like a tall order, but the technologies to achieve all of these objectives have been developed, prior to cancellations.

One thing is for sure: we can’t rely on designs that are half a century old, á la aviation pressure suits. Perhaps the biggest challenge facing suit design is the lack of direction for crewed space programs. It is relatively easy to design for a lunar mission when you know where your destination is, but designing for all scenarios without concrete direction can be expensive and time consuming.

The biggest challenge facing suit design is the lack of direction for crewed space programs

The Bio-Suit was invented by MIT Professor Dava Newman (pictured here) designed by Guillermo Trotti (A.I.A., Trotti and Associates, Inc., Cambridge, MA) , and fabricated by Dainese (Vicenza, Italy). – Credits: Donna Coveny